

Report No. 84FR9960

**UTILIZING THE GLOBAL
POSITIONING SYSTEM
(GPS) IN PROJECT
DESIGN, CONSTRUCTION
AND MAINTENANCE**

*By: Basharat Siddiqi, P.E.
Utah Department of Transportation
Development Engineer*

*Timothy J. Taylor, P.E.
Ryan R. Hales, P.E.
Ronald M. Hodge, P.L.S.
Glen J. Thurgood, P.E.
J-U-B Engineers, Inc.*

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DISCLAIMER

The findings, conclusions and recommendations contained in this report reflect the views of the authors who are responsible for the accuracy of the analysis and data presented herein. The contents do not necessarily reflect the official views of the Utah Department of Transportation or of J-U-B Engineers, Inc. This report does not constitute a standard, specification or regulation.

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UDOT RESEARCH & DEVELOPMENT REPORT

ABSTRACT

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ABSTRACT

This study, funded by the Utah Department of Transportation, identifies potential GPS users within the Utah Department of Transportation (UDOT) and the main activities to be enhanced through usage of GPS technologies. It compares the cost and person hours needed for selected activities using conventional survey techniques vs. GPS techniques, identifies improvements in UDOT's operations that may be achieved by implementing GPS techniques, and recommends implementation activities that should be initiated in relation to equipment, training, and other pertinent issues. A brief overview of GPS technology is presented. The report identifies benefits of GPS technology and general information related to GPS technology, quality control/quality assurance and cost recovery. Findings include substantial savings in time, increased cost-effectiveness, and increased productivity resulting from the use of GPS technology. Implementation recommendations include the establishment of a management/organizational entity to oversee the implementation of GPS technologies throughout the Department, purchasing of GPS Systems throughout UDOT, the development of standard GPS specifications and procedures, ongoing training for GPS users within the Department, the establishment of a GIS "data warehouse" for the collection and dissemination of GPS obtained data throughout the Department, and a follow-up mechanism to monitor quality, effectiveness, and performance issues.

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INTRODUCTION

State Departments of Transportation (DOT's) throughout the Country are facing an ever increasing challenge to develop and maintain transportation facilities so as to ensure the efficient movement of people and goods within communities, regions, and throughout the entire State. Budget and funding constraints constantly demand a less costly and more efficient means of carrying out this task while maintaining the same, if not a better level of accuracy, dependability, and ultimately quality of the end product. The health, safety and welfare of the general public are at stake.

A key component in the development and maintenance of these facilities is the accurate collection of location information. Accurate and dependable location information serves as a foundation for all State DOT projects. A project's success hinges upon the dependability of the location information. Conventional survey methods provide State DOT's with this information for use at the planning level and in pre-construction, construction, maintenance, etc.

Fortunately, technological advances continue to further our ability to complete tasks that at one time proved quite time consuming. Our ability to increase output is leading to a corresponding need to increase the input side of the equation. As a result, the need to collect location data with greater speed, and in greater quantities is also increasing. In all of this, accuracy must not diminish.

The end result is a need to collect location information with greater speed, increased accuracy, and less cost.

Recently, many State Departments of Transportation have begun using Global Positioning Systems (GPS) as an answer to this dilemma. GPS technology, primarily developed and implemented over the past ten years, can greatly reduce the time and costs associated with survey activities. This new approach is being used by more and more transportation agencies as a cost-effective means of collecting data necessary for transportation projects.

Project Scope

Within the Utah Department of Transportation (UDOT), the need to collect survey data quickly, accurately, and in a cost-effective manner has led to the development of this study. It is felt that GPS technology has numerous cost-effective applications within the Department.

The primary objectives of this study were to:

1. Identify potential GPS users within the Utah Department of Transportation (UDOT) and the main activities to be enhanced through usage of GPS technologies.
2. Compare the costs and person hours needed for selected activities using conventional survey techniques vs. GPS techniques.
3. Identify any improvements in UDOT's operations that may be achieved by implementing GPS techniques.
4. Recommend implementation activities that should be initiated in relation to equipment, training, and other pertinent issues.

In meeting these objectives, an extensive literature search was conducted in an effort to understand current applications and issues. Excerpts from the various literature sources are found throughout the report and a listing of references is found at the end of the report. The most useful, and most referenced report is NCHRP Synthesis of Highway Practice #258 entitled, *Applications of GPS for surveying and Other Positioning Needs in Departments of Transportation*, authored by Robert J. Czerniak, Ph.D. and James P. Reilly, Ph.D., published in 1998 by the Transportation Research Board ⁽¹⁾.

In addition to the study objectives, the report identifies benefits of GPS technology and general information related to GPS technology and quality control/quality assurance.

In preparing this report, it is important to note that several topics require additional research or work outside the scope of this study. As such, these items, issues, or topics are specifically mentioned throughout the report and are included in the Recommendations for Implementation section.

AN OVERVIEW OF GLOBAL POSITIONING SYSTEM (GPS) TECHNOLOGY

GPS technology was originally developed by the United States Department of Defense in 1973, with the first prototype being launched in 1978. Several systems including Block I (used to test and evaluate the prototype GPS system) and Block II (production GPS satellites) were developed and included the addition of satellites from 1978 to 1993, until the system was declared fully operational in 1994 ⁽¹⁾. This system is officially known as the NAVSTAR (Navigation System Using Time and Ranging) Global Positioning System, and is a full-time, all-weather, high-precision, earth-orbiting satellite positioning and navigation system ⁽¹⁾.

The entire GPS system actually consists of three "segments," including the space segment, the control segment, and the user segment. These different segments and their functions are summarized below.

Space Segment- The space segment consists of 32 satellites orbiting approximately 20,000 km above the earth in six separate orbits. These satellites are on a rotational time period of 11 hours and 58 minutes which allows a little more than two full revolutions in a 24-hour time period. Each satellite sends out radio signals that can be received on earth and used to measure the distance between the satellite and the observer. The satellites also send location information to control stations identifying their position and status, including any problems ⁽¹⁾.

Control Segment -The control segment consists of a Master Control Station located at Falcon Air Force Base near Colorado Springs, Colorado and four monitor stations located at various locations on the earth's surface. These stations track the satellites and compile detailed information about their clocks, orbits, and potential problems. This information is transmitted back to the satellites and then relayed to GPS users.

User Segment -The user segment consists of numerous portable GPS receivers (hardware), software and important detailed procedures needed to track satellite signals for surveying, navigation and other surveying needs for the military and civilian personnel. The user segment receives signals from the space segment and uses that information to compute a position anywhere upon the face of the earth with corrections from the control segment.

The 32 GPS satellites, often referred to as the GPS constellation, allow users to locate any point on the earth within a three-dimensional coordinate system using portable GPS receivers. The origin of this coordinate system is defined as the mass

center of the earth, which in turn is defined by the geoid model that is used. Locations are determined with varying degrees of accuracy and precision based on the quality of receiver being used and other operating principles applied to minimize errors. The satellites are positioned so that at least four are visible with good geometry all of the time from almost anywhere in the world. This allows GPS to function as a reliable location system ⁽¹⁾.

GPS technology operates on the basic principle of triangulation. If the distance from an observer to three known points can be measured, the position of the observer can be calculated. As long as the positions of referenced satellites are known at any given time and the distances to those satellites are measured using radio signals, the observer's position can be calculated.

In general, studies have shown that GPS work can be completed more quickly, at lower labor costs, and with greater accuracy than traditional methods. For these reasons, the Utah Department of Transportation views GPS as an attractive tool for use in transportation projects.

BENEFITS OF GPS TECHNOLOGY

Since the early 1990's when GPS was first being used as a survey tool, organizations have sought to determine whether or not GPS could be a viable tool. Departments of Transportation, other federal, state and local agencies, universities, and private companies have tested the technology in a variety of ways, seeking to compare GPS survey methods to conventional survey methods. For the most part, these activities have shown that GPS technology can result in better accuracy, increased person-hour productivity, and lower costs than conventional survey methods ⁽¹⁾. These and other specific benefits are outlined in this section.

Increased Productivity

GPS technology has been shown to substantially increase the productivity of a conventional survey crew. Conventional survey work is generally accomplished using a two or three-person survey crew. Under normal conditions, most GPS units can be operated by a single individual if needed. Many organizations have also concluded that the level of skill required to operate a GPS receiver unit is generally lower than that required to properly and efficiently operate a theodolite, EDM, or total station ⁽¹⁾, which reduces the initial labor costs associated with completing a survey.

In terms of field checks, there is no substitute for a field check on any form of survey data if the crew is remiss in their collection of data. However, a typical survey crew can collect more data in a shorter time with GPS and therefore reduce the total number of trips for the original collection. The New York State Department of Transportation reported that in three and one half years of GPS usage, over 250 highway projects were completed using this technology, and none of the surveys required a return to the site for additional observations ⁽²⁾. This isn't so much a benefit of GPS technology but of a good survey crew.

According to an NCHRP report on GPS use in transportation applications, labor reduction ratios for GPS as compared to traditional survey methods are commonly near 6:1 for horizontal surveys, and a 10:1 for elevation surveys ⁽¹⁾.

Research indicates that a one-person GPS crew is generally twice as fast as a conventional survey crew and, therefore, one GPS system with two units has the potential of being four times faster than conventional methods.

Michael Fazio, Region 4 Resident Engineer, indicated that a bench mark circuit that requires a week to complete using conventional methods takes 4-6 hours using the GPS system with an accuracy very close, if not better, than the conventional method.

The end result is the ability for conventional survey crews to increase both the quantity and quality of their work using a GPS system.

Time Savings

Closely related to increased productivity is the amount of time GPS technology can save. GPS project surveys can be completed in substantially less time as compared to traditional surveys as mentioned in the Increased Productivity section of this report.

Unlike traditional methods, GPS units only require line-of-sight to the sky in order to accurately locate points. Similarly, GPS surveys can be conducted in nearly every type of weather, including heavy snow, rain, or extreme temperatures. In the case of setting primary control for an average DOT project, GPS methods have shown total survey project time reductions of 4:1 ⁽¹⁾. Such time savings can be of extreme value in meeting project deadlines and efficiently using available resources.

Other advantages of using GPS technology include the ability to utilize the GPS system for long distances with few set-ups when compared to conventional methods. Once the GPS system is set, roving can be performed within a 6-mile radius of the base unit. With conventional methods, the total station would need to be moved about every 600 feet.

As a result, there is not a large mobilization time savings for the initial set up; however, the lack of subsequent set ups make significant time savings for the GPS.

Time savings are also realized through the added convenience of not needing to establish monuments, such as conventional methods or returning to the field to re-record field angles. Human error is reduced by using GPS since readings are not taken visually. Instead, by using GPS, the location is recorded electronically with minimal human interaction, other than selecting the location (point to record) and typing in a description of the point.

Since the GPS unit can work in inclement weather conditions where line-of-sight is not necessary, time and temporal seasons are not as important as they once were using conventional surveying methods that rely so heavily on line-of-sight. The repeatability of survey measurements is one of the very attractive issues with GPS.

Any time savings gained by using GPS can be reallocated to many other aspects of surveying (that are not currently being performed due to lack of person-power). The capability to perform year-round surveying can make the equipment useful during the long, wet winter months in the higher elevations. Typical surveying could include pre-construction/construction surveying, traffic and safety, maintenance, environmental,

right-of-way, and multiple GIS applications. Time savings alone using GPS are significant enough to warrant the use of the technology for as many applications as are possible.

Increased Accuracy

Industry standards are two centimeter accuracy for real-time horizontal GPS surveys. Vertical accuracy is approximately twice that of the horizontal accuracy. This is a sufficiently high level to accommodate most transportation survey uses. Other transportation applications requiring less accuracy or precision can be completed using resource grade units with accuracies on the order of one meter.

Studies have shown that as a general rule, horizontal GPS accuracy can exceed that of conventional survey methods by a factor of 5 or greater ⁽¹⁾. Vertical data collected with GPS units does have some limitations, however, as elevations obtained with GPS units can equal those collected by conventional methods in terms of accuracy, but not exceed them ⁽¹⁾. Recent advances in GPS technologies are resulting in highly accurate vertical measurements.

Many transportation applications aside from surveying do not require such a high level of accuracy, such as pavement and structure inventories or vehicle location. GPS accuracy is more than sufficient to accommodate these activities and a resource grade GPS unit can provide a more cost-effective alternative.

Applications of GPS surveying within Utah and Idaho indicate that accuracies obtained using GPS survey equipment are at least as accurate, and most likely, better than conventional methods. With a proper calibration, horizontal accuracies are better than conventional methods might yield, and the vertical accuracies are generally within 2-3 mm according to Michael Fazio in Region 4.

A survey conducted in Region 4 indicates that an open traverse between two HARN stations located 17 kilometers apart yielded accuracies within 1 mm vertically and 2 mm horizontally. The speed and accuracy of the GPS unit is unparalleled by the conventional methods, and therefore, leads to reduced user costs.

The Idaho Transportation Department recently completed a 20-mile open traverse in one day with an accuracy of 3 mm using GPS. With conventional methods, an open traverse of this magnitude would have taken one week to complete and the accuracy most likely would not have been in the same range as the GPS survey.

Cost Efficiency

The reduced costs associated with GPS surveys are generally due to decreased labor and time requirements. Conversion to GPS methods does require a substantial initial capital investment, however. Recent studies have shown that with such dramatic reduction ratios in terms of labor and time, the initial capital investment required for GPS tools can be recovered after only two or three large DOT project surveys ⁽¹⁾.

Surveys conducted in Utah and Idaho concur that decreased labor and time requirements can help defray the initial equipment costs. A good cost recovery system could be installed within the DOT that would help to recover the initial cost for the GPS units in a timely manner. Research has indicated that the initial investment cost of a GPS unit could be recovered within a one year time frame even if the unit is moderately used. More on cost recovery is found in the Potential Cost Recovery portion of the report.

POTENTIAL GPS APPLICATIONS

Within the wide range of work conducted by State Departments of Transportation, are many potential uses for GPS technology. While surveying projects appear to be the most logical place to implement GPS methods, other applications can provide increased efficiency and decreased costs to DOT users. Some examples of such applications where GPS may be of use include aerial photography and mapping, pavement and structure inventories, GIS database compilation and maintenance, and vehicle location programs.

Table 1 shows some divisions within the Utah Department of Transportation where GPS may be of benefit and specific applications where the technology may be used. These applications are further detailed in this section.

Table 1: Potential GPS Transportation Applications

UDOT	APPLICATION
Planning	<ul style="list-style-type: none">• Corridor Planning & Mapping• Right-of-Way Preservation
Construction	<ul style="list-style-type: none">• Topographical Surveys• Transverse Surveys
Preconstruction	<ul style="list-style-type: none">• Alignment Surveys
Maintenance	<ul style="list-style-type: none">• Features Inventory<ul style="list-style-type: none">- Structures- Signs- Pavements
Right-of-Way	<ul style="list-style-type: none">• Right-of-way Delineation• Property Identification
Traffic & Safety	<ul style="list-style-type: none">• Accident Reconstruction• Crash Statistics
Environmental	<ul style="list-style-type: none">• Features Identification• Planning-Level Inventories
GIS	<ul style="list-style-type: none">• Data Warehousing• Statistical Analysis

Planning

GPS may be used at the planning level for corridor mapping associated with short-and long-range improvement planning efforts in a cost effective and efficient manner. Preliminary surveying associated with alternatives evaluation and alignment

identification may most easily be accomplished using GPS. Right-of-way for future highways can be surveyed and preliminary alignments identified in preparation for subsequent corridor preservation activities. The use of GPS at the planning level may provide for more detailed and efficient evaluation of alternatives and development of improvement plans in a cost-effective manner.

The South Dakota Department of Transportation (SDDOT) conducted a study that demonstrated how a combination of GPS and current elapsed-distance technology can be applied to cost-effectively generate geographic coordinates for the existing Mile Reference Marker (MRM) based highway attribute data. This made the complete MRM attribute database usable in the State's developing GIS applications. The study also looked at application opportunities and preparation of a GPS technology implementation plan for consideration by SDDOT management ⁽³⁾.

Further research could be conducted on how to specifically apply GPS technology for use in long-range statewide corridor planning. From this, specific procedures could be developed for the collection of pertinent corridor information and the dissemination of the collected data to multiple divisions within the Department.

Construction/Preconstruction

The most widespread use of GPS technology in construction applications is in survey work. Skilled use of GPS units is more efficient than traditional methods using total stations, and can reduce survey time and costs. This can result in substantial project savings. For survey work, a geodetic-quality GPS receiver with centimeter-level accuracy is required. GPS can then be used to set project control, baselines, centerlines, continuous topography, utility location, boundary surveys, property surveys, slope staking, etc. GPS may not be accurate enough for the final grade of paved surfaces and may require the use of leveling to supplement the GPS established control. Control for structural projects can also be established using a survey-grade GPS unit. Ultimately, entire project surveys can be completed using GPS technology, reducing labor costs and time requirements for major roadway projects.

Maintenance

Maintenance operations may also benefit from the use of GPS units. Much of the data collection associated with roadway maintenance could be accomplished much faster using GPS technology. Pavement as well as structure inventories can be completed quickly, with GPS units being mounted in vehicles, and having much of the data collection work being completed from moving vehicles using the Real-Time Kinematic (RTK) features of GPS technology.

Sign inventories, along with the locations of cross drains, street lighting, signal poles, utility boxes, etc. could also be completed in a similar fashion. Currently, much of the data collection associated with these inventories is completed manually based on UDOT's highway reference system. This system uses roadside Reference Posts and Mileposts as its basis. These posts are often inaccurate or improperly placed, resulting in some error .

Using GPS receivers, maintenance inventories can be completed much more quickly and accurately than through manual methods. Since these inventories do not require survey-grade precision, less expensive GPS units with meter-level accuracy could be used for such activities. Person-hours required for this kind of survey would be reduced to the point where it would become cost-effective to use GPS, when it would have been cost prohibitive to use conventional methods.

Vehicle location is another GPS application as related to maintenance. Small, relatively inexpensive GPS units can be installed in snowplows or other maintenance vehicles. In the event that an emergency were to arise, these GPS units would provide a central dispatch center with the location of each vehicle within the DOT's maintenance fleet and the closest vehicle to the problem could be dispatched with very little delay.

One example application would be to implement this technology with the courtesy patrol currently monitoring the affected I-15 reconstruction corridors to prevent incident queue backup. The efforts of the incident management team could be coordinated with the traffic control center, allowing the dispatch of the vehicle closest to the incident the opportunity to respond and therefore, minimize the delay and queue backup. This could be done on a region or district level.

An April 1999 *Better Roads* article ⁽⁴⁾ describes an advanced winter maintenance truck prototype affixed with a global positioning system that provides constant location information and while a ROAR meter mounted to the truck reports the amount of friction between the tires and the road surface.

Another article from the December 1998 issue of *Roads and Bridges* ⁽⁵⁾ describes a demonstration project in Michigan that used an advanced global positioning system to shuttle snowplows from one end of the metro region to another, sending them where they were most needed during major winter storms.

Such technology has potential to make coordination of incident management and snowplowing efforts easier and facilitate a more cost-effective uses of resources.

Right-of-Way

Right-of-way surveys can also be completed in shorter time periods and at lower costs using GPS units as compared to traditional survey equipment. Time savings comes from fewer setups and a more rapid way of recording and obtaining points. Geodetic-quality GPS units can be used to locate property corners and right-of-way lines along streets and highways.

While no legal interpretation has yet been made on the accuracy of surveys completed using GPS units, it is probable that high-quality GPS receivers could be used to perform survey work associated with legal right-of-way and property descriptions.

On a planning level, use of resource grade GPS units would likely be acceptable for preliminary survey work and right-of-way identification associated with corridor planning and preservation activities. In the corridor planning level stages, GPS survey could help define an alignment that would reduce the impacts to the surrounding vicinity before a tight, very controlled and expensive right-of-way alignment was established for corridor preservation.

When planning for noise abatement procedures to be implemented along a corridor, some preliminary survey work needs to be completed in order establish the base elevation of the barrier to be placed, and to give the program some input as to where the road is located in relation to the dwelling units.

Traffic and Safety

Within the Traffic & Safety division, GPS units could be used in accident reconstruction and incident management. GPS units could be used to perform necessary survey work in accident reconstruction projects, including location of vehicles, obstructions, fixed objects and intersection/roadway geometry. This would make data collection easier, faster, and less costly in terms of labor costs and delay to other motorists experienced while waiting for accident crews to take pictures and measure skid marks, location of vehicles, etc.

In addition, as crash statistics are logged using GPS units, more precise locations can be determined, making later summaries more accurate and useful in programming highway safety improvements. Similarly, if all crash locations are recorded digitally using GPS units with meter-level accuracy, this information can be easily imported into a GIS database, making such data more readily accessible and useful to numerous interested parties.

Environmental

Environmental inventories can be completed quickly and more efficiently using GPS technology. Wetlands, specific habitats, plant locations, hazardous waste sites and flood plains can be identified and delineated for a multitude of uses including, selection of alternative roadway alignments, minimization of affected wetlands, threatened and endangered species, etc.

Locations of important cultural features including historical, paleontological and archaeological sites can be quickly identified using relatively inexpensive GPS units. This eliminates the need to perform labor intensive traditional surveying to locate features and improves the accuracy of the inventory as features are not referenced to roadside mileposts; instead they are referenced to real world coordinates.

This type of planning-level environmental inventory is vital to long-range corridor planning and improvement programs. GPS units could make this planning-level data collection and feature inventory work less expensive and more accurate due to labor and time cost savings.

A study sponsored by the Federal Highway Administration and conducted by the Virginia Transportation Research Council ⁽⁶⁾ looked at the feasibility of using GPS to capture environmental field data. During the study the accuracy of data collected in diverse environments was tested. Findings indicated that data collection was accurate and conversion of the data in GIS or CADD formats was practical. The report concluded that GPS technology is a highly feasible way to capture environmental location data.

Geographic Information Systems (GIS)

The Utah Department of Transportation is currently in the process of developing and updating their GIS database. This system contains information about much of the state transportation system. Traditionally, this information has been linked to the state highway reference system using the existing roadside reference posts and mileposts.

State transportation officials are currently in the process of developing a GIS system containing all of this information. Resource grade GPS units with meter-level accuracy would be extremely valuable in collecting data and location information to be used in this GIS system.

Geographic information such as crash statistics, structure locations and conditions, pavement condition, roadway geometry (width, material, superelevation and length), roadway jurisdictional ownership, reference posts, sign inventories, and other

data could be collected using GPS receivers and later imported into UDOT's GIS database. This would be a much more cost-effective method of data collection and would allow the state GIS database to be maintained more frequently and at a lower cost. Information about the state transportation system would then be more accurate and easily accessible to users, both within UDOT and from the outside community.

Applications not Conducive for GPS

It should be noted that with the use of GPS technology and the implementation within the DOT, conventional methods have not become useless. Many applications remain where conventional methods will yet be used.

When it is necessary to perform surveys in locations where satellite occlusion might prevent the reception of the necessary number of satellites for an accurate measurement, conventional methods need to be used. Examples of such situations include but are not limited to, surveying existing abutments under a bridge structure, tunnels, surveys performed next to tall buildings or in forests with thick or tall vegetation and by lakes.

UDOT RESEARCH COMPARATIVE ANALYSIS

Included within the scope of this research project was a budget allowance to purchase GPS equipment that would be used to complete a comparative analysis with conventional surveying methods. It was determined by the UDOT ISS Department that a Trimble 4700/4800 RTK system be purchased including and antenna with groundplane, HI rod, OSM II battery charger, 6 Ah battery, Trimble TS office software, GPS survey software, and a 4700 base carrying case. The 4800 rover kit with internal radio includes, a range pole with three lithium batteries, battery charger, a TSC1 data logger, a Trimmark II base radio, 4700 backpack, 2 M fixed height range pole with bipod legs and a 4700 camcorder battery cable. This equipment was originally allocated to the UDOT Region 4 office located in Richfield, Utah.

During the past several months, the Region 4 Construction Survey Crew has been using the GPS equipment to repeat surveys in locations where he had previously used conventional methods and where a person-hour comparison could be made.

In a control and topography survey conducted with both conventional and GPS methods the time savings alone was 14 times greater using the GPS method. Further discussion regarding UDOT's comparative analysis is found in the Cost/Benefit Comparison section of the report.

QUALITY CONTROL AND QUALITY ASSURANCE

Essential to the success of GPS technologies is the establishment of a system for assuring the quality of the data being collected. It is very important to understand potential sources of error associated with GPS technologies, to develop a set of standard GPS survey specifications for both Department and third-party surveys, and to develop standard procedures to be followed based on the type of survey being performed.

Potential Sources of Error

Similar to conventional survey methods where the accuracy is only as good as the techniques used to obtain them, GPS methods have the same difficulty to overcome. Error sources for GPS work are many and can be avoided or compensated to produce accuracies better than a conventional methods might yield.

The following is a discussion of the most common sources of error encountered using GPS technologies.

Selective Availability

The Department of Defense can deliberately downgrade the accuracy of the GPS satellites signal through a process called Selective Availability (SA). They reduce the accuracy available to unauthorized users in times of war or for military action. With the recent military efforts in Kosovo, several times during the peak bombing raids SA was implemented and the satellite signal distorted with induced errors from the Department of Defense providing a desired decrease of accuracy.

Several methods can be undertaken to produce this type of reduced accuracy to the signal, one method is dithering the satellite clock or offsetting the orbit data. Authorized users may obtain encrypted information to correct clock and orbit information so that accuracies are not affected during these times ⁽¹⁾.

Range Errors

These types of errors are related to the range or distance between the receiver and the satellite at the time that the measurement was taken. This measurement is known as "pseudorange" before any corrections have been made to correct the errors that will improve the positional accuracy ⁽¹⁾.

Clock Errors

Two sources of clock errors can be encountered; the satellite clock error with respect to the GPS time and the receiver clock error with respect to the satellite clock. Generally, clock errors cancel out when using relative positioning techniques ⁽¹⁾.

Orbital Errors

The GPS receiving antenna is dependent upon the distance from the satellite and the coordinates of the satellite at the instant of measurement. Orbital errors affect the calculated position of the antenna. There are several components associated with orbital errors: radial error-the calculated distance from the mass center of the earth; along track error-shifting up or down within the orbital track; and out of plane error-lateral displacement from the orbital plane. With relative positioning, orbital errors tend to cancel out ⁽¹⁾.

Ionospheric Errors

The layer of the atmosphere that is between 50 km and 1000 km above the surface of the earth is known as the ionosphere. This is the layer of atmosphere where the sun ionizes the gases within this level to differing intensities depending on the state of sun spot activities. Due to the differing ionized gasses in this level, the satellite signals get bent or delayed while traveling through this level. Since the diffraction is greatest when the satellites are low on the horizon, it is not a recommended practice to track a satellite that is within a 15° angle above the horizon ⁽¹⁾.

As one could imagine the ionospheric errors tend to be greater during the daylight hours as the gas particles are charged with energy from the sun. When using short baselines with relative positioning techniques the ionospheric errors tend to cancel out ⁽¹⁾.

Tropospheric Errors

Similar to the ionospheric errors, the tropospheric errors are created by refraction and affect the signals from the satellites. These errors are magnified by the low tracking angle above the horizon. As with the ionospheric errors, a short baseline and relative positioning techniques tend to cancel out the refraction errors encountered within the troposphere ⁽¹⁾.

Multipath Errors

These types of errors are caused by reflections of the GPS satellite signals bouncing off buildings, lakes, etc. which elongate a normally direct signal path (range).

Typically, antennas that are used for geodetic surveys are designed to minimize the effects of multipath and are sensitive to low reflective angles. Unfortunately, this type of error does not cancel out and is sensitive to the location of the antenna with respect to reflective surfaces ⁽¹⁾.

Geometric Errors

In order to receive accurate information, the position of the satellites with respect to the receiver is vital in GPS. The problem is similar in nature to the triangulation or trilateration in conventional surveys and is referred to as "Dilution of Precision" (DOP). DOP is a dimensionless number that represents the relative strength of the satellites positions with respect to the receiver position. A useable scale of DOP numbers range from one to ten, with five or less being the preferred ⁽¹⁾.

Obstructions

Anything that can block the satellite signal is considered to be an obstruction. In some cases a single large object such as a building can obstruct the view of several satellites at one time and render the survey mission useless. This becomes more apparent when only tracking the minimum number of satellites required. Careful planning should be undertaken to minimize the potential signal blockage from the receiving antenna for geodetic surveys ⁽¹⁾.

Antenna Phase Center

The vertical coordinate component of a geodetic survey could be off due to a variation in the location of the antenna phase center. This phase center is where the focus of the received signals are measured to and how elevations are calculated. This location is much like the Height of Instrument (HI) in conventional surveying ⁽¹⁾.

Development of Specifications and Procedures

In order to ensure uniformity among a group of GPS users, standards and procedures must be developed.

To begin with, general specifications and procedures may be adopted, and as work proceeds, they can be tailored to fit specific crews, types of surveys, etc.

Specifications may include such items as the type of GPS receivers, tripods, and antennas required, the number of project reference stations, the minimum number of GPS control points, the technique to be used in establishing bench marks, the applicable vertical reference system, and data collection times.

Not only will the Department want to develop their own set of specifications, but specifications for third-party surveyors should also be developed. Where independent consultants are used to perform GPS surveys, control reports are often required for each job completed ⁽²⁾. A control report includes such items as:

- A network diagram displaying the observed and processed independent vectors.
- A tabular schedule showing each station's occupancy times and sessions.
- Data about the processed vector quality, including loop closure results.
- The minimally constrained adjustment results and analysis.
- Each station's adjusted coordinates.
- A survey accuracy statement, per Federal Geodetic Control Committee (FGCC) specifications.
- Complete indication of relevant horizontal and vertical datums and control stations.
- Clear identification of base stations used to process kinematic observations.
- A comprehensive listing of GPS receivers, antennas, and processing and adjustment software.

Procedures assure accurate positions of survey points within acceptable tolerances. It is extremely important to note the fact that errant positional solutions can and are derived by improper field techniques and are very difficult to detect ⁽⁷⁾. Procedures may include information relative to the type of receiver required, the minimum number of available satellites, specific settings related to the survey controller configuration, how to's on collecting "topo" points, etc.

A key to successful quality control and quality assurance is the development of a structured, standard approach to planning, organizing, and conducting GPS control surveys in a wide variety of circumstances and environments.

Further research regarding the establishment of standards and procedures is highly encouraged as a part of the GPS implementation process.

COST/BENEFIT COMPARISON

One of the key advantages of using GPS technology is that it can produce substantial cost savings (time & labor) as compared to traditional survey methods. As previously mentioned, the time savings on the Snow Canyon survey approximately 14 times greater using the GPS over conventional survey methods.

UDOT Cost/Benefit Comparisons

To quantify the benefits of using GPS methods over traditional survey crews, UDOT conducted several field surveys in Region 4 in central Utah using GPS techniques. Results of these GPS surveys are summarized in Table 2 below in terms of project length, man-hours required, and number of points recorded.

Table 2: UDOT Region 4 GPS Survey Summaries

Project Location	Project Size	Survey Type	Man Hours	No. Points
SR-20	20 miles	Control & Topographic	30	558
Baker Canyon	7 miles	Control & Topographic	30	660
Meadow I-15	15 miles	Control & Topographic	50	4,470
Richfield Main St.	4 miles	Control	3	7
SR-24 / SR-62	2 miles	Topographic	4	2,388
Aurora Right-of-Way	3 miles	Right-of-Way	10	22
Dog Valley Gravel Pit	1 x 1 mile	Property	10	34
Snow Canyon	2.75 miles	Topographic	30	5,511
Bluff & Sunset Drive	1 mile	Control & Topographic	30	1,969
Dog Valley I-15	8 miles	Control & Stake Out	25	150
Kannaraville	1 x 1 mile	Property	10	24

To truly evaluate the savings realized through the use of GPS equipment, time spent conducting GPS surveys must be compared with time spent on similar surveys using traditional methods.

As an example, consider the survey of Snow Canyon, listed in Table 2. This survey consisted of 5,511 topographic points recorded using GPS equipment and was completed in 30 person-hours. By comparison, a similar survey was conducted by UDOT in Snow Canyon in 1997 using traditional methods. This 1997 survey consisted of 1,500 topographic points and required 120 person-hours to complete.

Assume that an average two person survey crew bills at \$80.00 per hour. Applying this rate to the person-hours spent on the snow canyon survey yields a GPS survey cost of \$1,200.00 and a conventional method surveying cost of \$4,800.00. It is important to point out that the GPS survey recorded 3.7 times the data points in 1/4 of

the time. The comparison between the two surveys is shown below in Table 3.

Table 3: Snow Canyon Survey Comparison

Survey Type	Person-Hours	No. Points	Efficiency Ratio (pts/hr)	Cost to perform survey
GPS	30	5,511	183.7	\$1,200
Traditional	120	1,500	12.5	\$4,800

If the conventional survey was placed on a comparative level to collect 5,511 points as the GPS survey had collected (using the 12.5 pts/hr), it would take 441 hours and cost \$35,280.00 to perform.

As shown in Table 3, collection of topographic points as part of the Snow Canyon survey was accomplished much more quickly using GPS techniques as compared to conventional methods. In this instance, the person-hour reduction ratio was approximately 14:1.

General Cost/Benefit Comparisons

In other studies and other states, labor reduction ratios have been found to commonly range from 6:1 to 20:1 for these types of surveys ⁽¹⁾. This magnitude of time and labor savings results in substantial cost savings for project survey work and allows transportation departments to quickly recover the initial capital investment required to purchase GPS equipment.

Other organizations, including state transportation departments and private consultants, have conducted similar comparisons of GPS and standard survey methods. The New York State Department of Transportation (NYSDOT) began an initial GPS survey project in June 1994, which included establishing the New York High-Accuracy Reference Network (NYHARN), a control network for later GPS surveying.

NYSDOT then began using GPS receivers on highway survey projects and have completed over 250 such projects using GPS as of early 1998. None of these projects required a return to the site for additional observations or field checking ⁽²⁾.

Private consultants have also turned to GPS units to complete survey work and have found the reduced labor cost savings beneficial. Along with the reduced labor cost savings, the added speed of obtaining GPS points makes it possible to obtain more points in a single day, and therefore, leads to more surveys being completed in a year's time.

Potential Cost of Recovery

Given the time and labor cost savings involved with using GPS for survey data collection vs. conventional methods, it is possible to recover the cost of the initial investment in a relatively short amount of time.

Private firms have recovered the complete cost (< \$100,000.00) of their GPS systems in as short a time as one year as a result of being able to do more work in a shorter amount of time.

In a situation where cost recovery is not physically achievable, as would be the case with a State DOT, theoretical cost recovery based on time savings and increased productivity easily justify the initial purchase.

IMPLEMENTATION

It is important for any organization, public or private, to develop a sound strategy for implementing GPS technologies. The numerous potential applications of GPS technology require that organization and coordination be conducted not by a specific division but a GPS individual/team who can allocate resources on a broad basis. The information provided up to this point in the report serves as the motivation required to initiate the process. Some of the essential implementation elements include an understanding of the issues related to funding, equipment, training, organization/management entities, follow-up, and data warehousing.

Funding

As with any capital investment, the initial question to be answered is, "Where do we get the money?" Implementation Statewide may represent a substantial capital investment. Purchasing a few units at a time will spread the initial investment yet purchasing everything at once generally qualifies the buyer for a reduction in the overall cost per unit.

A few follow-up questions might include, "Is the money allocated to each region for purchase of the equipment?" or "Are federal monies involved?" and "If so, what process needs to be followed to obtain the funding?". Questions such as these need to be answered in order to establish a funding mechanism to begin the purchase of new GPS systems.

Equipment

The equipment decision is generally based on two factors: accuracy and cost. In terms of accuracy, a features inventory will most likely not require the same accuracy as would be required for setting control. In terms of cost, GPS systems used to collect features inventory data will be less expensive than those used to set control.

It is important to identify needs among the various potential users initially prior to purchasing GPS equipment. Doing so may result in a substantial cost savings to the Department.

Resource Grade GPS System

A resource grade GPS system is typically used for such applications as a features inventory. Published accuracies are submeter for horizontal and twice that for

vertical. Where accuracy is not as important, resource grade units can be purchased for around \$10,000.

Survey Grade GPS System

A survey grade GPS system is typically used where accuracy is key to the success of the survey. In terms of cost, a survey grade unit may be purchased for around \$50-\$60,000. This cost includes a single base unit and one rover. Additional rover units will cost approximately \$25,000 each.

Currently, there are a variety of GPS vendors. The equipment purchased as a part of this research project is considered to be "top of the line" survey grade unit. A Trimble 4700/4800 RTK system was purchased and includes an antenna with groundplane, HI rod, OSM II battery charger, 6 Ah battery, Trimble TS office software, GPS survey software, and a 4700 base carrying case. The 4800 rover kit with internal radio includes a range pole with three lithium batteries, battery charger, a TSC1 data logger, a Trimmak II base radio, 4700 backpack, 2 M fixed height range pole with bipod legs and a 4700 camcorder battery cable.

Research has shown that this "top of the line" equipment is recommended by many GPS users and should be considered as the industry standard for accuracy, durability and ease of use. As with any technology, the system will need to be maintained properly to ensure the desired accuracies are achieved.

Training

Most GPS vendors offer training courses on using GPS technologies. Trimble offers training on the equipment purchased by UDOT as part of this research project. Typically, training courses can be arranged at the user's site and accommodate up to 20-30 users at a relatively low cost compared to individual training sessions.

Other training opportunities are provided through local training centers and could be conducted on a regular on demand basis.

Learning Curve

Most conventional surveyors adapt quickly to using a GPS system. Depending upon the background of the user, the learning curve can range from 6 months to a year. After a year most surveyors are pushing the limits of the GPS system and have a very good understanding of the technology. The greatest amount of time is spent learning and understanding potential sources of error.

With technology moving forward at lightning speed, it is very important for GPS users to invest time into researching current applications, maintaining contact with additional users, and attending frequent training courses when offered. It has been estimated that a person can expect to spend up to 10 hours a week keeping pace with changes in GPS technology.

Organizational/Management Entity

An organizational/management entity should be implemented to oversee GPS usage throughout the Department. Differences among potential users may create difficulties in scheduling and resource allocation if the task of GPS coordination is assigned exclusively to anyone existing division.

Organizational items to be considered by this entity may include Regional coordination, GIS data warehousing, equipment purchasing, training, resource allocation, quality control/quality assurance, specifications, procedures, and inter-division coordination.

Implementation Follow-up

On-going monitoring of such items as cost/benefit, productivity, time savings, etc. will provide valuable information needed to perform annual updates regarding successes and failures of the GPS systems and at the same time present problems or areas of concerns, etc. A solid understanding of these factors will in turn provide a GPS team with the information they need to revise specifications and/or procedures, adjust schedules, re-allocate resources, etc.

Data Warehousing

GPS systems have the capability of allowing users to collect very large amounts of data. However, the big question is, "Once the information's collected, what do you do with it?" A complete database of survey data, inventories, etc. could prove highly beneficial if it were made available to multiple users.

For example, as surveys are completed, districts or regions may forward their data to a GIS person/team who would archive and store the data for future use within that region, and potentially to any DOT division. An example would include using survey data collected in 1999 to more accurately prepare a cost estimate for an overlay project on the same roadway in 2010. There are numerous applications where archived GPS data could be used in future applications.

The specifics related to the implementation of a GIS data warehouse go beyond the scope of this report. More than likely it would require the preparation of a GIS master plan to address the current and future direction of GIS Department wide.

FINDINGS

In this section of the report a summary of the significant findings are repeated and summarized for review.

- Departments of transportation, other federal and state and local agencies, universities, and private companies have tested the technology in a variety of ways, seeking to make comparisons between GPS and traditional survey methods. For the most part, these activities have shown that GPS technology can result in better accuracy, increased person-hour productivity, and lower costs than conventional survey methods ⁽¹⁾.
- Research indicates that a one-person GPS crew is generally twice as fast as a conventional survey crew and, therefore, one GPS system with two units has the potential of being four times faster than conventional methods.
- Labor reduction ratios for GPS as compared to conventional survey methods are commonly near 6:1 for horizontal surveys, and 10:1 for elevation surveys ⁽¹⁾. One GPS unit and one person can produce the work of a conventional two person crew under normal circumstances.
- In the case of setting primary control on an average DOT project, GPS methods have shown total survey time reductions of 4:1 ⁽¹⁾.
- Applications of GPS surveying within Utah and Idaho indicate that accuracies obtained using GPS survey equipment are at least as accurate and most likely better than conventional methods.
- The key advantage of using GPS technology is that it can produce substantial cost savings (time & labor) as compared to traditional survey methods.
- Recent studies have shown that with such dramatic reduction ratios in terms of labor and time, the initial capital investment required for GPS tools can be recovered after only two or three large DOT project surveys ⁽¹⁾.
- GPS surveying techniques have application in most all DOT divisions including planning, construction, preconstruction, maintenance, right-of-way, traffic and safety, environmental, etc.
- A key to successful quality control and quality assurance is the development of a structured, standard approach to planning, organizing, and conducting GPS control surveys in a wide variety of circumstances and environments.

In no way is this list of findings exhaustive as related to the numerous findings discussed throughout the report, within the literature reviewed, or resulting from the field studies conducted by the Department.

The list is intended to present those findings that include information relative to substantial savings in time, increased cost-effectiveness, and increased productivity resulting from the use of GPS technology.

Additional findings regarding implementation are presented in the following section, Recommendations for Implementation.

RECOMMENDATIONS FOR IMPLEMENTATION

During the course of this research it has become apparent that recommendations for implementation are appropriate based on the study findings and may help enhance the implementation of a formal Department-wide GPS program.

- It is recommended that an organizational/management entity be established to oversee GPS usage throughout the Department. Differences among potential users may create difficulties in scheduling and resource allocation if the task of GPS coordination is assigned exclusively to anyone existing division.

Organizational items to be considered by this entity may include Regional coordination, GIS data warehousing, equipment purchasing, training, resource allocation, quality control/quality assurance, specifications, procedures, and inter-division coordination.

- It is recommended that a GPS team develop standard specifications for utilizing GPS within the Department as well as for third-party surveyors. This could be accomplished as an additional research activity. The specifications would undergo a series of modifications from the original document as regions develop specifications based on unique geographical conditions.
- It is recommended that GPS management develop or have developed standard procedures in a manner similar to the specifications.
- It is recommended that equipment needs be identified for each division and region. For construction/pre-construction activities, survey grade GPS units would be essential. For other uses such as planning and maintenance, resource grade GPS units may be sufficient.
- It is recommended that the Department purchase the same survey grade equipment purchased as a part of this research project, mainly a Trimble 4700/4800 RTK system including an antenna with groundplane, HI rod, OSM II battery charger, 6 Ah battery, Trimble TS office software, GPS survey software, and a 4700 base carrying case. The 4800 rover kit with internal radio includes, a range pole with three lithium batteries, battery charger, a TSC1 data logger, a Trimmak II base radio, 4700 backpack, 2 M fixed height range pole with bipod legs and a 4700 camcorder battery cable.

In terms of resource grade GPS units the Trimble XR or XRS is recommended.

Trimble has proven to be a leader and a maker of good, quality survey products for many years and have continued the tradition with their GPS survey equipment.

- It is recommended that the Department request and organize formal training to be provided either by the manufacturer of the GPS equipment or by a third party training provider to all current/potential GPS surveyors. This could take place as a one time course involving 20-30 persons at some central location or a series of ongoing workshops that keep pace with changing technologies. Over time, the development of an in-house training program may be appropriate.
- It is recommended that a GIS database be expanded or developed to accommodate a "GPS data warehouse" where all GPS data could be pooled and be made available throughout the Department. This topic should be further expanded as a part of a future research project.
- It is recommended that, as a start, GPS technologies be implemented primarily for the purpose of conducting surveys associated with preconstruction/construction activities. More specific research may be appropriate in regards to implementing GPS technologies for the use in the specific areas of planning, maintenance, traffic and safety, environmental, right-of-way, and GIS.

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